FAST RESPONSE LIQUID CRYSTAL CELL RETARDER SYSTEM

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Background of the Invention.

This invention relates to optical retarder devices, and particularly to fast response liquid crystal cell optical retarder systems and polarization control systems.

In optical devices, instruments, communication systems and laboratory set-ups, it is often desirable to be able to selectively vary the retardance of one polarization component of a light beam relative to another, orthogonal component so as to vary the total polarization of a light beam. This has typically been accomplished using optical wave plates disposed parallel to one another wherein the polarization is varied by rotating the fast axis of one wave plate with respect to the fast axis of the other. In fiber-optic communication systems, polarization adjustability has been accomplished typically by mechanical devices that squeeze, or otherwise stress the fiber, so as to change its birefringent properties.

Polarization can also be selectively controlled by the use of a liquid crystal cell retarder. In such devices, the phase of light polarized along one axis with respect to another, orthogonal axis

varies in accordance with the amplitude of an applied ac voltage. This characteristic has been employed in optical shutters, as disclosed in Box U.S. Patent No. 4,635,051, issued January 6, 1987 and entitled "High-Speed Electro-Optical Light Gate and Field Sequential Full Color Display System Incorporating Same," and in polarization control systems, as disclosed in Rumbaugh et al. U.S. Patent No. 4,979,235, issued December 18, 1990 and entitled "Polarization Controller for Use in Optical Fiber Communications System" and Clark et al. U.S. Patent No. 5,005,952, issued April 9, 1991 and entitled "Polarization Controller," all of which patents are herein incorporated by reference in their entirety. However, where used to vary polarization by switching between intermediate values over a range of retardances, known liquid crystal cell retarder systems have two significant drawbacks.

First, a change in retardance in one direction must be effectuated by the application of an increased ac voltage, but the response speed of the retarder in that direction is limited by the responsiveness of the liquid crystal cell material. Second, a change of retardance in the other direction must be effectuated by reducing the applied voltage and allowing the liquid crystal material to relax back to a new retardance; that is, it cannot be driven by the application of a voltage. These two drawbacks greatly limit the response speed of a liquid crystal cell retarder and, therefore, the applications to which the retarder may be put.

3

In particular, the slow response time of known liquid crystal cell retarder systems limits the speed with which they can switch between intermediate values, and corresponding polarization states, over a wide range of retardances. This limits their effectiveness in producing rapid changes in light polarization in optical instruments and laboratory set-ups, and in controlling polarization and fiber-optic communication systems where significant polarization fluctuations may occur. Accordingly, there is a need for a liquid crystal cell retarder system which provides a faster response time.

Summary of the Invention

The aforementioned need for a fast response liquid crystal cell retarder system has been met by the present invention through the use of a technique referred to herein as "impulse switching," and through the use of stacked, "opposing" retarders. It has been discovered that the rate at which a liquid crystal cell retarder switches from one retardance to another retardance under the influence of an electric field increases with increased applied voltage. The present invention employs this characteristic to decrease the switching time by initially applying a switching voltage higher than the voltage corresponding to the target retardance so as to cause the liquid crystal cell to move toward that target retardance at a rapid rate. Then, before, or substantially at, the time when the target retardance has been reached, the applied voltage is switched to the voltage corresponding to that target retardance, and maintained until a new

retardance is desired. The term "impulse switching" used herein refers to the application of a voltage in excess of the voltage corresponding to the target retardance.

While impulse switching can be used to decrease the switching time of a liquid crystal cell retarder in one direction, the change back to the retardance in the other direction in a single cell ordinarily is accomplished by relaxation of a liquid crystal material. To decrease the switching time in the other direction, two "opposed" liquid crystal cells are used, the fast axis of each of the liquid crystal cells being disposed at $\pi/2$ radians to one another. The total retardance of both cells will therefore be the difference between the retardances produced by the two cells. Consequently, the retardance can be switched positively in one direction by application of a higher voltage to one cell and positively in the other direction by application of a higher voltage to the other cell. Impulse switching is applied to both cells to obtain the maximum switching speed in both directions.

Since liquid crystal cell retarders have retardance limits, the voltages across each of the opposed cells cannot be increased indefinitely. However, it has been discovered that the retardance relaxes in a substantially linear manner for the large part of the period of relaxation from one retardance to another. The present invention takes advantage of this feature by reducing the voltage on both cells simultaneously between switching events to zero, or some other acceptable bias voltage. This allows the cells to drift back to

retardances corresponding to a lower voltage simultaneously and, since the total retardance is equal to the difference between the respective retardances, the total retardance does not change.

For situations where the time between desired changes in retardance is shorter than the time required for the two liquid crystal cell retarders to drift back to a new, adequate bias point, a second pair of opposed retarders may be stacked on the first. These can be used to switch the retardance rapidly while the first pair of the stack is drifting to a new bias point. An appropriate algorithm may be provided, under digital processor control, to maximize the speed that both pairs of opposed retarders adjust the total retardance through this retarder system. Yet additional pairs of opposed retarders may be added to the stack to decrease further the delay time between retardance switching.

The afore-described embodiments of the retarder system are incorporated in a rapid response closed loop polarization control system. They are also incorporated in a fiber-optic communications link.

The foregoing and other objectives, features, and advantages of the invention will be more readily understood upon consideration of the following detailed description of the invention, taken in conjunction with the accompanying drawings.

Brief Description of the Drawings

Figure 1 is an illustration of a liquid crystal cell retarder, showing two eigen-axes, an ac drive signal source and two polarization components of a light beam before and after passing through the retarder.

Figure 2 is an illustration of a typical liquid crystal cell retarder showing a cross-section, including an ac drive signal source.

Figure 3 is a graph of the retardance of a liquid crystal cell retarder as a function of voltage.

Figure 4 is a graph of the retardance of a liquid crystal cell retarder as a function of time upon the application of a step function voltage for three different voltages.

Figure 5 is a graph of retardance of a liquid crystal cell retarder as a function of time following the step function reduction of a voltage applied to that cell for two different reductions in voltage.

Figure 6A shows the RMS amplitude of a rectangular waveform ac voltage pulse to be applied to a liquid crystal cell retarder.

Figure 6B shows the retardance of a liquid crystal cell retarder as a function of time in response to the ac voltage pulse of figure 5A.

Figure 6C shows the RMS amplitude of an ac voltage pulse applied to a liquid crystal cell retarder according to the principles of the present invention.

Figure 6D shows retardance of a liquid crystal cell retarder as a function of time in response to the ac voltage pulse of Figure 6C.

Figure 7 shows an ac drive signal circuit for a liquid crystal retarder system according to the present invention.

Figure 8 shows an ac voltage drive signal generated by the drive signal circuit of Figure 7.

Figure 9 shows an opposed liquid crystal cell retarder system according to the present invention.

Figures 10A - 10I illustrate a typical sequence of application of drive voltages to an opposed liquid crystal cell retarder system according to the present invention.

Figure 11 shows a stacked, opposed liquid crystal cell retarder system according to the present invention.

Figure 12 shows a liquid crystal cell retarder integrated into a fiber-optic link according to the present invention.

<u>Detailed Description of the Invention</u>

As shown in Figure 1, a typical liquid crystal optical retarder comprises a liquid crystal cell 10 and a drive signal source 12, which supplies a relatively low voltage ac drive signal. The cell 10 has two eigen-axes, that is, a fast axis 14 and a slow axis 16. Liquid crystal material is optically anisotropic and, when properly contained within a liquid crystal cell, is birefringent; that is, its index of refraction along one axis perpendicular to the axis of propagation of light through the cell is different from its index of refraction along another axis perpendicular to the axis of propagation of light through the cell. The eigen-axes of the cell are, by definition, orthogonal

to one another. One axis is known as the fast axis because its index of refraction is the closest of the two indices to 1; that is, it is the axis along which light travels the fastest. Since light travels slower along the other eigen-axis it is known as the slow axis. As a practical matter, due to the anisotropic nature of liquid crystal material the indices of refraction along the two eigen-axes ordinarily are not likely ever to be equal.

The index of refraction along one of the axes of a typical liquid crystal cell of the type employed in the present invention can be varied by application of a relatively low voltage ac signal, the index of refraction being a function of the amplitude of the ac signal, as is commonly known in the art. Ordinarily, it is a non-linear function of the RMS amplitude of the ac signal. Thence, the degree of birefringence of the cell can be controlled by control of the amplitude of the ac signal applied by the drive signal source 12. Which of the two eigen-axes has an index of refraction controlled by the applied ac voltage depends on the construction of the liquid crystal cell.

As shown in Figure 1, light propagating along axis 18, from left to right for example, can be considered as having two components of polarization, that is, a fast axis component 20 and a slow axis component 22. The amplitudes and phases of these components depend on the polarization of the propagating light relative to the axes, the electric field vector of the light representing that polarization being resolved along the two eigen-axes. In the example shown, it is

9

assumed that the fast axis and slow axis define a cartesian coordinate system 23, the fast axis being at 0 radians and the slow axis being at $\pi/2$ radians, and that the light arriving at the cell from the left is linearly polarized with an orientation of $\pi/4$ radians with respect to the coordinate system 23. Thence, upon entering the cell 10, the fast axis polarization component 20 of the light is equal in magnitude to the slow axis component 22, and they are in phase with one another.

In the example shown in Figure 1, when the light entering the cell 10 from the left emerges from the right, the slow axis component 22 has been delayed relative to the fast axis component 20 by some amount Γ, known as the retardance. This delay is caused by the birefringence of the cell, and results in a change in the polarization of the emerging light. Since the birefringence of the cell can be controlled by controlling the amplitude of the ac signal, the amount of retardance and the polarization of the emerging light likewise can be controlled by controlling the amplitude of the ac signal. In the example, the slow axis component has been delayed an amount which causes the light emerging from the cell 10 to be elliptically polarized, as is commonly understood in the art.

Turning now to Figure 2, a liquid crystal cell 11 according to the present invention is preferably constructed of a pair of substantially-parallel transparent plates 24 and 26 made of glass (though other material could be used without departing from the principles of the invention), liquid crystal material 28 being sandwiched therebetween. While nematic liquid crystal material is

10

preferred, twisted nematic material will work, and other liquid crystal materials may also work without departing from the principles of the invention. Transparent electrodes 30 and 32, made of indium tin oxide, for example, are disposed on the inside surfaces of the plates 24 and 26, respectively, and a drive signal source 13 is connected to those electrodes. Alignment layers 34 and 36, typically made of rubbed polyimid or sputtered silicon monoxide are disposed on the insides of the electrodes 30 and 32, respectively, to align the liquid crystal material adjacent the plates 24 and 26, as is commonly understood in the art. Preferably, spacers 38 and 40 are disposed at the edge of the cell to keep them separated a predetermined distance. The construction and operation of such a liquid crystal cell is well understood in the art.

It is to be understood that, while a liquid crystal cell of this type is preferred, other types of liquid crystal cells may be used without departing from the principles of the invention. It is also to be understood that, in practice, the cell 11 may actually only be a part of a larger element, such as an array or stack of cells in a liquid crystal display.

Preferably, the drive signal source 13 provides a rectangular waveform having a 50% duty cycle, that is, a square wave. This is because, while the breakdown voltage of the liquid crystal cell is a function of the peak voltage of the applied signal, it has been found that the rate at which liquid crystal material will change its alignment, and thereby change its birefringence, in response to an

applied signal is a function of the RMS voltage of the applied signal. Since the RMS voltage of a square wave signal is higher than the RMS voltage of a sine wave signal, for a given peak voltage, a square wave signal produces a shorter response time than a sine wave. Other waveforms may be used, however, without departing from the principles of the invention.

The dimensions of the cell 11, that is, the spacing 42, the plate thickness 44 and size 46 (that is, the height and width, or diameter), may vary considerably, depending on the application. Minimum spacing will tend to minimize response time, while the range of retardance that can be adjusted with the cell becomes less with closer spacing. In addition, in most applications requiring high purity polarization, it is counterproductive to introduce any optical discontinuities, such as would be caused by spacers, so edge spacing may be important. At the same time, where edge spacing is used and a relatively large cell is needed, the plate thickness must be great enough to maintain a substantially constant spacing throughout the interior of the cell.

As has been mentioned above, both the change, and rate of change, in birefringence of the cell 11 are functions of the applied RMS voltage. Thence, the retardance Γ produced by the cell is a function of the applied RMS voltage, as shown by Figure 3, and the rate of change of that retardance is also a function of the applied RMS voltage, as shown by Figure 4. Figure 4 shows a graph of the retardance of a typical cell 11 as a function of time upon the application of a step function voltage (RMS) for three different

12

voltages. Upon the application of voltage V1 (5 volts), the retardance changes from 3.4π radians to $\pi/2$ radians in 35 milliseconds. However, upon the application of voltage V3 (20 volts), the same change in retardance takes only 2.3 milliseconds.

While an increase in applied voltage drives a change in liquid crystal birefringence, a change in birefringence in the opposite direction, that is, relaxation to a lower voltage state, is not driven by the applied voltage. However, it has also been found that the rate of relaxation of liquid crystal material to a lower voltage state is affected by the applied voltage. As can be seen in Figure 5, which shows a graph of retardance of the cell 11 following the step function reduction of the voltage applied to that cell, when changing from the retardance corresponding to voltage V4 to the retardance corresponding to voltage V5, the cell would take time T1. If the applied voltage is reduced below voltage V5 to voltage V6, the retardance curve extends further to the right so that the cell will relax faster over the same voltage range, taking only time T2, which is less than T1. Preferably, the voltage V6 would be zero. In any case, the relaxation of the cell retardance over the useful range is essentially linear with time. An impulse switching feature of the present invention is illustrated by Figures 6A through 6D. First, the response of a conventional liquid crystal retarder system is shown in Figures 6A and 6B. Figure 6A shows the application of an ac voltage pulse (volts RMS as a function of time), and Figure 6B shows the response of the conventional retarder to that pulse (retardance, Γ as

13

function of time). It can be seen that when the voltage pulse changes from voltage V7, corresponding to the initial retardance Γ_1, to voltage V8, corresponding to a target retardance Γ_2, the time for the cell to switch retardances is T3. When the pulse falls back to voltage V7, the relaxation time is T4.

However, as shown by Figures 6C and 6D, according to the present 64H invention to change the retardance from Γ_1 to Γ_2 the applied voltage 64H is first switched to voltage V9, until the retardance reaches Γ_2, then it is switched to voltage V8. That is, the applied signal is first switched to a voltage higher than that corresponding to the target retardance long enough, or nearly long enough, for the target retardance to be reached, then switched to the voltage corresponding to the target retardance to maintain that retardance, taking into account the voltage rise and fall time limitations of the drive circuitry. As a result, the time T5 for the retardance to change from 64H Γ_1 to Γ_2 is much less than in a conventional system. Preferably, the applied signal would be switched initially to the maximum allowable voltage so as to attain the maximum rate of change of retardance. The portion of the drive signal waveform occurring during the switching of the liquid crystal in response to a voltage increase is referred to herein as the switching impulse, and has a duration referred to herein as the switching impulse period.

64H Similarly, to return to retardance Γ_1, the applied signal is B 64H switched to 0 volts, until Γ_1 is reached or nearly reached, then it is switched to voltage V7. That is, the applied signal is first switched

14

to a lower voltage (preferably 0 volts) than that corresponding to the relaxation target retardance until that retardance is reached or nearly reached, then it is switched to the voltage corresponding to that target retardance to maintain that retardance. Consequently, the relaxation time T4 is reduced significantly. The portion of the drive signal waveform occurring during the relaxation of the liquid crystal is referred to herein as the "relaxation impulse," and has a duration referred to herein as the relaxation impulse period.

It is to be recognized, of course, that in practice the retardance may be switched between many different, often random, values using the same principles of this invention.

A block diagram of a drive signal source 13 according to the present invention is shown by Figure 7. It comprises an ac signal source, preferably a square wave generator 48, a waveshape control unit 50 and an amplitude modulator 52. The square wave generator produces a square wave voltage at an appropriate frequency as is commonly understood in the art. The waveshape control unit produces the switching waveshape, that is, it provides the RMS voltage applied signal waveshape. This circuit would either include data representative of the empirically or analytically determined response characteristics of the liquid crystal cell 11, so that the time to impulse switch from one retardance to another can be predicted, or it would include a feedback control circuit responsive to the change of polarization of light passing through the cell to determine when the target retardance is reached so as to switch from the impulse voltage

15

to the voltage corresponding to that target retardance. Preferably, this would be accomplished by digital processing, though analog processing may be appropriate in some cases. Ordinarily, the waveshape control circuit would either include, or be responsive to, a circuit for determining what the target retardances should be, depending on the particular application. The amplitude modulator 52 modulates the signal produced by the square wave generator 48 to produce an ac drive signal having the envelope for the required RMS voltage as, for example, the drive signal shown in Figure 8.

An opposing retarder system for driving a change in retardance either from a low retardance to a high retardance or vice-versa by an increase in voltage according to the present invention is shown in Figure 9. This embodiment comprises a first liquid crystal cell 54 and a second liquid crystal cell 56, both of which are preferably like liquid crystal cell 11. The fast axis 58 of cell 54 is aligned at 0 radians and the slow axis 60 is aligned at $\pi/2$ radians relative to coordinate system 61; however, the fast axis of cell 56 is aligned at $\pi/2$ radians while its slow axis 60 is aligned at 0 radians. Consequently, the total retardance Γ_T produced in light propagating along propagation axis 66 passing through both cells is Γ_1 minus Γ_2, that is:

$$\Gamma_T = \Gamma_1 - \Gamma_2$$

Since Γ_1 can be decreased by increasing the drive signal applied to cell 54 and Γ_2 can be decreased by increasing the drive signal applied to cell 56, the total retardance Γ_T can be either increased or

decreased by an increase in the voltage applied to one of the two cells, thereby taking advantage of the faster rate of retardance switching as compared to retardance relaxation. Moreover, by employing the impulse switching feature of the present invention along with this opposing retarder feature, the total retardance can be changed even faster.

In addition to the first cell 54 and the second cell 56, the opposing retarder system shown in Figure 9 includes a first drive signal generator 68 and a second drive signal generator 70, respectively, for applying drive signals to the cells, as described with respect to liquid crystal cell 11. It also includes an opposed retarder control circuit 72, which is connected to each of the first and second drive signal generators to provide them with control signals which govern their drive signal wave shapes. Thence, for example, assuming that the retardance of a given liquid crystal cell decreases with increasing drive voltage and vice-versa, to decrease total retardance the opposing retarder control 72 will cause the first drive signal generator 68 to increase the drive signal voltage to the first cell 54; to increase the total retardance, the control circuit 72 will cause the second drive signal generator 70 to increase the drive signal voltage to the second cell 56. Since this cannot go on indefinitely, the cells having maximum, breakdown voltages, the drive signal voltages must periodically be reduced simultaneously to allow

17

the retardances to relax back to lower voltage states, as explained hereafter.

The operation of the opposing retarder system according to the present invention is explained more specifically, and by way of example, with respect to Figures 10A through 10I. In order for a given cell to increase or decrease the retardance from its quiescent state, the cells are ordinarily biased by a bias voltage V_{bias}, corresponding to a predetermined retardance at the middle of the retardance adjustment range. Assuming that the cells have a retardance range of 2π radians, they would typically be biased at π radians of retardance, as shown in Figure 10A. Ideally, the midpoint 74 between the retardances of the two cells would be kept at the bias point to provide maximum adjustability in either direction at any given moment. That cannot be done, because the retardances of the cells cannot be relaxed back to their starting retardances instantaneously. However, they can be allowed to relax back simultaneously without changing the total retardance significantly, because, as has been pointed out above, the relaxation of retardance is essentially linear with time.

Accordingly, to change the total retardance from 0 radians, as in Figure 10A, to $\pi/2$ radians, as in Figure 10B, the voltage applied to second cell 56 is increased. Then, the voltage applied to both cells is simultaneously reduced so that both cells will relax back by $\pi/4$ radians of retardance, thereby moving the midpoint 74 back to the bias value, as shown in Figure 10C. To increase the total retardance $\pi/2$

radians further, the voltage applied to the second cell is increased again, as shown in Figure 10D. Then, to return the midpoint to the bias value, the voltage applied to both cells is reduced an amount corresponding to an increase of $\pi/4$ radians of retardance. To reduce the total retardance by $\pi/4$ radians the voltage applied to the first cell is increased, as shown in Figure 10F. Then, to return to the bias value, the voltages applied to both cells are reduced, as shown in Figure 10G. To return to 0 total retardance, the voltage applied to the first cell is increased again, as in Figure 10H, and the voltages applied to both cells are then simultaneously reduced to return the midpoint 74 to the bias value (the midpoint in this case being equal to the bias value).

Thence, it can be seen that, by increasing one or the other of the drive voltages and thereafter reducing them simultaneously, the total retardance can be switched rapidly in either direction indefinitely, provided that sufficient time is allowed between total retardance switching for the cells to drift back far enough for the next change in total retardance. Preferably, the impulse switching feature of this invention will be used to reduce these times even further.

Notwithstanding that relaxation time for a liquid crystal cell can be reduced by the techniques of the present invention, the relaxation time is much longer than the switching time for voltage increases. This means that there will be occasions when a single pair of opposed cells cannot be switched from a first retardance to a

19

second as quickly as other times because the new retardance is beyond the switching limit, given the current position of the midpoint, so that there will be a delay until the midpoint has relaxed far enough. To reduce this delay, one or more additional pairs of opposed liquid cells may be stacked along an axis of propagation 76, as shown in Figure 11. Thence, a first pair of opposed cells 78 and 80 are provided with respective drive signal circuits 82 and 84, which are controlled by a stacked opposed retarder control circuit 86, and additional such pairs up to N pairs, represented by cells 88 and 90 and respective drive circuits 92 and 94, are also controlled by the control circuit 86. The total retardance Γ_T is then the sum of the retardances for all of the pairs; that is, in the example shown:

$$\Gamma_T = \Gamma_1 - \Gamma_2 + \Gamma_3 - \Gamma_4.$$

When the retardance adjustment limit for one pair is not great enough for a needed adjustment and the time for that pair to relax to a midpoint that would increase that limit adequately, another pair can be used to switch the retardance, thereby reducing the delay interval by one half. To reduce that delay even further, additional cell pairs may be used, the delay time being reduced by a factor of 1/N, where N is the number of cell pairs.

The principles of the present invention may be employed in a closed loop state of polarization system, particularly one for fiber-optic communications. A system of this type which employs three liquid crystal retarders and a closed loop control system for endless polarization control is described in the aforementioned Rumbaugh et

20

PB al. U.S. Patent No. 4,979,235. The retarders of that system would be replaced with retarders according to the principles of the present invention.

In addition, retarders according to the principles of the present invention may be integrated into a fiber-optic link, as shown in Figure 12. In this embodiment of the invention one or more liquid crystal retarder cells are disposed in a package 114 which is pigtailed to an input fiber 116 and to an output fiber 118. The input fiber 116 is coupled to an input graded index ("GRIN") lens 120, and the output fiber 118 is coupled to an output GRIN lens 122. The retarders are disposed between the input and output lenses. For example, the link would include a first cell 124, a second cell 132, and a third cell 136. Light from the input fiber 116 is coupled by the input lens 120 to the first cell 124, and light from the third cell 136 is coupled through the output lens 122 to the output fiber 118. Each of the cells is controlled by drive signal circuitry according to the principles of the present invention.

The terms and expressions which have been employed in the foregoing specification are used therein as terms of description and not of limitation, and there is no intention in the use of such terms and expressions of excluding equivalents of the features shown and described or portions thereof, it being recognized that the scope of the invention is defined and limited only by the claims which follow.

4